Beyond The Sky: artificial intelligence in robotic surgery for missions to Mars and possible developments on Earth

Pantalone D. MD, F.A.C.S.[1], Faini GS.[2], Cialdai F[3], Sereni E[3], Morbidelli L[4], Bacci S[5], Bani D[6], Bernini M[7], Pratesi C[8], Stefano PL[9], Orzalesi L[10] and Monici M[11].

[1] Fellow of the American College of Surgeons, Core Board and Head for studies on traumatic events and surgery in the ESA-TopicalTeam on “Tissue Healing in Space: Techniques for promoting and monitoring tissue repair and regeneration” for Life Science Activities Agency. Assistant Professor in General Surgery, Dept of Experimental and Clinical Medicine, University of Florence, Specialist in Vascular Surgery, Emergency Surgery Unit - Trauma Team, Emergency Dept – Careggi University Hospital, Florence (IT)

[2] Dept of Experimental and Clinical Medicine, University of Florence, Careggi University Hospital, Florence (IT)

[3] PhD, Degree in Biological Sciences, Scientific Researcher ASA campus joint laboratory, ASA Res. Div., Dept of Experimental and Clinical Biomedical Sciences “Mario Serio”, University of Florence, Florence (IT)

[3]PhD, Degree in Natural Sciences, Fellowship at ASA campus joint laboratory, ASA Res. Div., Dept of Experimental and Clinical Biomedical Sciences “Mario Serio”, University of Florence, Florence (IT)

[4] PhD, Associate Professor of Pharmacology, Dept. Life Sciences, University of Siena

[5]ScD, PhD.Senior Researcher, Dept of Biology, Research Unit of Histology and Embriology, University of Florence, Florence (IT)

[6] Full Professor of Histology, University of Florence, Italy, Dept. Experimental & Clinical Medicine; Sect. Anatomy & Histology, Research Unit of Histology & Embryology Florence, (IT), Head for studies on clinical diagnostics and histology in the ESA-TT on “Tissue Healing in Space: Techniques for promoting and monitoring tissue repair and regeneration” for Life Science Activities

[7]PhD - Breast Surgery, Breast Unit, Oncology Department, Careggi University Hospital, Florence, (IT)

[8] Full Professor of Vascular Surgery. Director of the School in Vascular Surgery -Dept of Experimental and Clinical Medicine-University of Florence, Director of the Vascular Surgery Unit, Cardio -Thoracic and Vascular Dept - Careggi University Hospital, Florence (IT)

[9] Associate Professor of Cardiac Surgery, Director of the School in Cardiac Surgery -Dept of Experimental and Clinical Medicine-University of Florence, Director of the Cardiovascular Surgery Unit. Cardio-Thoracic and Vascular Dept - Careggi University Hospital, Florence (IT)

[10] Associate Professor of General Surgery, Department of experimental and Clinical medicine, University of Florence, Italy, Director Breast Unit, Oncology Department, Careggi University Hospital, Florence, Italy

[11]Degree in Biological Sciences. Scientific researcher Manager of ASA Res. Div-ASA Campus joint laboratory, Dept of Experimental and Clinical Biomedical Sciences “Mario Serio”, University of Florence, Florence (IT), Coordinator ESA-TT for “Tissue Healing in Space: Techniques for promoting and monitoring tissue repair and regeneration” for Life Science Activities Agency.

Introduction

From “Minimally Invasive Expeditionary Surgical Care using Human-Inspired Robots” report of the Blue Sky Meeting, Pensacola (FL), October 2018 (1):

“In transit to Mars: “*Astronaut develops abdominal pain associated with nausea, vomiting, and fever. A low grade leukocytosis is identified on laboratory evaluation: probable diagnosis is appendicitis. Pain and mild tenderness localize to the right lower quadrant (RLQ). Abdominal ultrasound (US) imaging confirms an abnormal, dilated structure in the RLQ consistent with acute appendicitis. The astronaut is treated with antibiotics and intravenous hydration resulting in partial resolution of symptoms. Within a week, the astronaut develops a higher fever and increased RLQ pain. Repeat US imaging reveals a probable peri-appendiceal abscess. The crew medical officer (CMO) prepares the abdomen for abscess drainage as the assistant prepares the instruments and positions the US probe. With US imaging for guidance, the CMO inserts a percutaneous needle under local anesthesia. Needle aspiration reveals pus from the suspected abscess. Using the Seldinger technique, a guide wire is slid through the needle to the site of the abscess then the needle is removed. Using a #11 blade scalpel, the CMO makes a small incision along the wire, then slides a multiport drainage catheter over the wire to the location of the abscess. The wire is withdrawn and suction is applied to the catheter draining the abscess. Antibiotics and catheter suction are continued for a week. The drainage finally decreases and the catheter is removed. The small wound from the drainage catheter heals with daily change of the Band-Aid. There are no sequelae, and after a course of rehabilitation, the astronaut returns to normal duty for the duration of the mission.”*

There are several unique features of this scenario that may not be readily apparent. The CMO is not a surgeon, but has been trained pre-flight (with periodic in-flight refresher sessions) on advanced health care techniques including the minimally invasive surgical (MIS) placement of a drainage catheter. The medical/ surgical assistant for the CMO (who manipulates the US imaging probe and assists with the drain placement) is not a human crew member, but ***an interactive, human-inspired dexterous robot****. Both the CMO and the robot assistant use integrated augmented reality images of the patient’ s abdominal contents to evaluate and guide the anatomic placement and advancement of the needle and drain insertion. The #11 scalpel blade was part of the conventionally manifested medical supplies, but the* *handle for the scalpel blade was printed on demand for the procedure, matched to the human and robotic manipulator dexterity, using the space craft's multi-material 3-D printer. These unique abilities do not currently exist as described for space flight, but are reasonable to anticipate for exploration space missions within the next two decades "*

Among future missions to Mars (2), a first landing on the red planet is scheduled for 2030 and the first human settlement in 2032. The health of the astronauts, during the long journey to the planet and after landing, is a major concern due to the prolonged and extreme stress conditions to which their body will be subject.(3) Unforeseen events or issues requiring surgery could jeopardize the entire mission and pose a risk to the life of crew-members.(4,5) To date, the presence of an experienced surgeon in the crew is the most desirable option but it cannot be taken for granted. In a paper by Martin et al (6), it is explained that in deep space class missions, the onboard health care provider needs to be near the patient, supported by ground based surgical advisors, plus data store forward transmission (6-8), still image exchanges , voice conferencing, and electronic chats. An "intelligent medical system" will assist the CMO with the diagnosis, monitoring and treatment of sick crew members (3,6-8*).* In case of particularly challenging events the CMO can turn to an onboard dedicated library for support (6) but he/she may still benefit from any other technological advance, as, for example, a new generation robot. In the future, space robots are expected to have a higher degree of autonomy in performing tasks like surgical procedures as suturing or providing help in diagnostics. The definition of Autonomy, according to the International Organization for Standardization (9), is: "an ability to perform intended tasks based on current state and sensing without human intervention". Their evolution in space surgery and the new achievements related to "artificial intelligence" (AI) are of great interest not only for space, but also for possible terrestrial clinical applications (10).

An "intelligent" robot for surgery in space

Presently, robotic surgery is characterized by the presence of a human operator in charge of high level planning or cognitive decision making, while the robot is responsible only for the mechanical implementation (11).

As the primary health care provider aboard the spacecraft to Mars , the CMO, is not a flight surgeon who shall be sitting on a remote console on Earth, an intelligent medical system will necessarily be required to assist the CMO with the diagnosis, monitoring, treatment of sick or injured crew-members. The system shall also guarantee CMO clinical skills maintenance, assistant officer training and crew skills practice. (6)

The literature reports on technological improvements that open up new perspectives and devices for example Robonaut 2 (13), a new generation of humanoid robot, the Trauma Pod (14), the SOLACE project (15).

Robonaut 2 (R2)(13)

The goal of this project is to develop intelligent robots for use in medical procedures. Researchers at the NASA Johnson Space Center (JSC), in collaboration with General Motors and Oceanering, designated this highly dexterous, humanoid robot, for employment in a variety of medical applications, from telemedicine to medical management either in teleoperation or autonomous mode .

Since current concepts for space exploration mission anticipate a small crew size, from four to six astronauts, the question that needs to be addressed is whether a human-inspired, dexterous robot could serve as an effective medical and surgical assistant.

The Florida Institute for Human and Machine Cognition (IHMC) organized a specific meeting 'Blue Sky Meeting' in Pensacola, Florida on October 2-3, 2018, supported by the Translational Research Institute for Space Health, with the primary goal to explore the role of a robot in surgery during exploration spaceflights. The symposium offered an excursus on the possible use of this human-inspired robot as effective medical-surgical assistants and on advances in space surgery[45]. The conclusion was that, for now, more investigation on the topic needs to be developed.

The Trauma POD (14)

The Trauma Pod (TP) is a rapidly deployable robotic platform to perform critical diagnostics and emergency life-saving procedures. Born for military use on wounded soldiers who might otherwise die before treatment in a hospital, now the platform should be used for avoiding the loss of airways , controlling hemorrage through hemostasis, inserting intravenous or intraosseous lines, manipulating damaged tissue and positioning monitoring devices (14).

Initially, the robotic TP system was tested by performing selected surgical procedures on a patient phantom. The teleoperated surgical robot is supported by autonomous robotic arms and subsystems that carry out the main scrub-nurse and circulating-nurse functions such as change tools and supply delivery. This system also includes a tomographic X-ray facility two-dimensional (2D) fluoroscopic devices to support interventions. (14) Any clinical protocol generated in the TP system is recorded automatically. Thirteen subsystems are present. The Surgical Robot System (SRS) is capable of performing basic surgical functions (e.g. cutting, dissecting, and suturing) through teleoperation. The other systems are capable of autonomously serving the SRS (for example the Scrub Nurse System-SNS) and recording every TP activity.

If an error occurs, all subsystems revert automatically and manual intervention by a remote administrator is required. System tasks are initiated by the surgeon and interpreted by the User Interface System (UIS).(14) The surgeon has direct control over the SRS through voice commands and a teleoperated joystick interface. In the TP system there are two major cells: a *control cell*, where the surgery is controlled by the surgeon and monitored by the administrator, and a *surgical cell*, where the surgery is performed by the TP subsystems. The *control cell* includes a control station for the surgeon and one for the system administrator, multiple displays of video and sensory information. The *surgical cell* contains all the TP subsystems required to perform surgical procedures.(14)

Some procedures have been tested on a phantom in a controlled environment, for example a bowel-closure or a shunt-placement procedure with no human assistance. In this phase of experiments the goal was to demonstrate the practicability of performing robotic surgery remotely without medical staff in the operating theatre. The first target was to verify the feasibility of conducting robotic surgical procedures via teleoperating mode. The second target was to perform full-body CT scans in the field during the operation. The user interface allowed the effective control of the system, and no intervention from the user administrator (human) was required. The interaction with the system felt 'natural' to the surgeon and allowed him to concentrate on the surgical tasks. A video of the procedure was recorded automatically. (14)

Beyond teleoperation, TP technology may change some aspects of practices in the operating room.

At the time of this experiment (14) the system demonstrated that all the robots and devices are integrated through a software layer presenting unified information and control interface to the surgeon. Incorporating automation in the operating room may serve to implement and lead to:

• Integrate all the medical devices in the operating room, enabling interaction with a single user.

• Integrate imaging equipment and data with surgical robotic equipment to perform minimally invasive, image-guided procedures.

• Archive and correlate relevant information and events occurring during a surgical procedure.

• Perform surgical procedures in remote locations where there is no medical personnel.

However many issues must be taken in account, like sterilization and cleaning of each subsystem, the fact that there is a number of skills that the system must be able to perform for completing a full surgical procedure, the requirement of anesthesia performance skills the management of multiple manipulators, the system robustness and so forth and so on.

The Solace project (15)

A space evolution of the Trauma Pod project is the SOLACE project (Space Orbiting Lifeboat and Medical Care during Evacuation project). This project is a high-fidelity simulation of an emergency beginning on the lunar surface. The medical ship in lunar orbit has the task to promptly retrieve injured astronauts from the surface and provide onboard medical care. The final destination for definitive cure is the Earth. This medical "life boat" is designed to provide "role 2 and 3 care" according to military roles of assistance. The Roles are numbered 1-4 and have the following tasks: Role 1 is the first responder treatment to be executed on the lunar surface. Required immediately after an injury to stabilize a patient for transport to an appropriate facility, this type of care is provided by trained corpsmen and medics, the military counterparts of paramedics. Role 2 is primary care, trauma management and emergency medicine, and is provided by the emergency room. Role 3 encompasses resuscitation, wound surgery, damage control surgery and postoperative treatment. Role 4 is the final treatment before an eventual return to duty status and would be provided on Earth once the transit is complete. In short, SOLACE in space serves as a navy hospital ship having an emergency room, surgical facility, and in-patient care center. The aim is to stabilize the patient for ascent and provide as much critical care as possible during the "golden hour" of trauma.(15) A portable diagnostic equipment is available, as well as medication and basic hemostatic agents. After the lunar ascent, the Trans Earth Injection begins. In transit, autonomous monitoring and responsive Total Parenteral Nutrition (TPN) is used to stabilize and give the appropriate fluids and nutritional support to the injured astronauts while he/she is returning to Earth.(15) The application of this project to NASA's Human Exploration of Mars Design Reference Architecture (DRA) 5.0 could be a blueprint for future deep space missions. This experience on the proximity of the Moon will provide a high-fidelity simulation of a deep space mission, and the evaluation of performances of critical system.(15)

SOLACE is also capable of a "plug and play" for a module compatible with NASA's interplanetary spacecraft architecture.(15) A Hercules lander could be used to retrieve injured crew members and the Trans Earth Injection (TEI) module is resident in the Mars Transfer Vehicle design. Onboard medical equipment would be autonomous or teleoperated. The objective is to gradually come out from the teleoperation mode, to reach the autonomous mode as technology matures. SOLACE design would also incorporate a Lifting Body Reentry Vehicle to minimize g-forces on injured crew members during Earth atmospheric reentry.

Conclusion

Mars Missions will last approximately 3 years,(2) considering voyage and time spent on the planet, hence surgical emergencies or trauma are more likely to occur. A surgical dedicated robot in space is a desirable opportunity for the crew and CMO, that should be provided with an image-guided autonomous system, ultrasound, magnetic resonance imaging or computed tomography scans. It should also be pre-programmed to perform basic surgical procedures, like suturing, but also other issues as real-time decision-making, anaesthesia support, vital-signs monitoring, and post-operative care (10). Any improvement and modification promoted by "artificial intelligence" applications, as well as miniaturization of devices shall be desirable both for space surgery and health care. The Robots' features shall therefore be increasingly adapted to the tasks they will be progressively called to perform.

In a paper of 2019, Panesar et al (10) wrote that the next generation robots are expected to have the ability "to see", "think" and "act" without manned intervention to achieve a surgical goal in a safe and effective way. The robot must perform 2 intrinsic functions: the first is to accomplish the preprogrammed goal of the procedure; the second is to be able to dynamically respond to an ever-changing surgical environment.(10) In other words, it has to go through the mapping of its perception to begin with and then plan efficient actions for the future.

Machine learning (ML) , which is part of AI, is the ability of a machine to learn from prior experiences.(10) However, analyzing multimodal sensory information to mimic a human surgeon's perception in real time is a much more complex action than applying AI algorithms, for example to a radiological scan for diagnostic purposes.

Besides, a robot must be taught how to perform surgery. This is a difficult task because mimicking a human surgeon effectively requires not only the ability to detect and interpret all relevant sensory inputs and positional information, but also to have a database of explicit knowledge on how to safely proceed to achieve the surgical goal.(10) It must be remembered that in space, in addition to this limitation, the communication delay may render teleoperational mode unfeasible (16,17). The CMO or crew medics may also not have the appropriate medical training to encompass all the full range of potential pathologies explorers may encounter. A fully autonomous surgical system may be a possible choice, if the technology is available. Otherwise, a partially autonomous approach may be used, as in the STAR trials (18) in which the crew has a minimal medical training to be able to perform the initial and final phase of a surgical procedure, whereas the robot performs the more complex phases. However we are presently far from the creation of such a robot, that could be expected for the end of the 21st century according to the Authors (10). In this case AI combined with surgical robotics shall be capable of optimizing surgical outcomes and improve access to care. It is already a fact, however, that all the improvements and new discoveries stemming from space research, for example the Smart Robot "Brain Surgeon" (19), the " MRI and CAT scans" (19), the "Multi-layer Microcapsules Help Drug Delivery/Fight Tumors" (19) and others that are commonly used in every day life, have many applications that can benefit life on Earth.

ACKNOWLEDGMENT:

The Authors thank Dr Patrizia Agresti, Registered Translator at the Courthouse of Florence, for her help in checking and revising the English version of this manuscript.

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